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Final Report

Contract NAS5-31747

Prepared for:

National Aeronautics and Space Administration
Goddard Space Flight Center
Earth Sciences Procurement Office
Greenbelt, MD 20771

Tropospheric Modeling Improvement

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1. Rationale and Objectives

For geophysical applications such as measuring global sea level rise or postglacial rebound, three-dimensional site position motion must be found with an uncertainty of at most 1 mm/yr. In order to attain geodetic results with this accuracy, it is necessary to accurately determine the atmospheric propagation delay component of delays measured by very long baseline interferometry (VLBI) or by the global positioning system (GPS) [MacMillan and Ma, 1994]. The largest source of remaining unmodeled error in determining site heights is this atmosphere delay component.

During our DOSE investigation, we have examined the modeling of tropospheric delay in VLBI and GPS geodetic analysis. Our work can be divided into three areas of investigation. The first was to compare VLBI and GPS atmospheric delay estimates and to reduce the errors that depend on the elevation angle of observations. VLBI and GPS observations made at low elevation angles are used to reduce the correlation between estimates of the site vertical and the zenith tropospheric delay. On the other hand, lower elevation observations pass through more atmosphere resulting in larger atmospheric modeling errors. Two ways of addressing this problem are to improve the atmosphere models and to determine the optimum minimum observing elevation angle.

The second area of study involved using GPS troposphere estimates as an atmosphere calibration in VLBI processing rather than estimating the atmospheric delay from VLBI data. This method has the advantage that one would no longer need to make VLBI observations at very low elevation angles since the atmospheric delay is not estimated.

In the third area of investigation, we compared horizontal atmospheric gradients derived from GPS and VLBI measurements since we have found that modeling these gradients improves the precision and accuracy of VLBI results. GPS simultaneously observes several satellites at different positions in the sky, whereas VLBI can only observe one quasar source at a time. This means that the atmospheric delay retrieved by GPS may be different than from VLBI if azimuthal variations in the atmosphere are present. Using lower elevation observations also means that VLBI measurements are affected by atmospheric refractivity variations over a larger horizontal spatial scale than GPS.

2. Summary of Results

1. VLBI and GPS Troposphere Comparisons and Reduction of VLBI and GPS Elevation-angle Dependent Errors

We have compared GPS and VLBI zenith tropospheric delays for the two-week CONT94 series of NASA R&D experiments for 5 sites with collocated GPS and VLBI antennas to determine their relative accuracy and precision. The two techniques agree to about 5-6 mm rms delay (about 50% greater than the formal uncertainty). [MacMillan and Elowitz, 1994]. We found that VLBI and WVR (water vapor radiometer) zenith wet delays agree at a comparable level. There are biases between the GPS and VLBI troposphere estimates that vary from day to day. Over the two-week period, the rms scatter of the daily biases were 2-4 mm depending on the site. Errors of this size in the VLBI or GPS zenith troposphere would result in site vertical errors of from 5-12 mm. A by-product of the zenith wet delay estimates is precipitable water (or column-integrated water vapor content), which is derived by an approximate linear relationship. The zenith wet delay accuracy based on VLBI and GPS comparisons translates into about 0.15 g/cm² of precipitable water. This level of accuracy is sufficient to be used in numerical weather prediction, which requires an accuracy of 0.1-0.2 g/cm² of precipitable water.

Atmospheric modeling errors are elevation dependent and can introduce systematic errors into site position estimates. A mapping function gives the dependence of tropospheric delay on the elevation angle at which a quasar source (VLBI) or a satellite (GPS) is observed. The precision of VLBI site vertical determinations is improved by about a factor of two when the minimum observing angle is reduced from 15° to 7°. For DOSE, we investigated errors in the mapping functions that are used in VLBI or GPS geodetic analysis [Gipson, 1995]. This study put bounds on the expected size of site vertical error due to mapping function error as a function of minimum elevation observed. We showed that the optimum minimum elevation was 7° to 8°. Expected errors in the mapping functions result in vertical errors of 5 mm at 7° and 2-3 mm at 10°. We began work on determining site-dependent mapping functions.

We have also examined other non-atmospheric GPS elevation angle dependent errors in order to be able to separate them from the effects of atmosphere modeling errors. One of these errors is multipath error. We have performed tests with the IGS GPS antenna at the Goddard Geophysical Observatory (GGAO) to determine the elevation angle dependence of multipath error and have tried different methods for mitigating its effect. Multipath here is caused by signal scattering effects from the concrete pier on which the antenna is mounted and by the ground. Multipath effects were reduced by a factor of 2-3 when multipath fixes were applied [MacMillan and Clark, 1995; Clark and MacMillan, 1995]. These methods are inexpensive and relatively easy to apply and could be used for the many GPS antennas that are mounted in a similar way.

2. VLBI Atmospheric Delay Calibration Using GPS Atmosphere Estimates

Several years ago, our group was involved in work to use wet zenith delays derived from water vapor radiometer measurements as an atmospheric delay calibration

for VLBI instead of estimating the atmosphere from the VLBI data. There was some success, but it was not cost-effective to put WVRs at every VLBI site. In our DOSE work we found that the alternative idea of using GPS atmosphere estimates as a VLBI calibration has some promise. We found that for certain VLBI sites, the geodetic precision of site position estimates was improved markedly by up to 50%, whereas, at other sites results were worse. Our current conclusion is that data from weaker VLBI antennas with less than ideal observing (less sensitive antenna or worse sky coverage) can be strengthened by using GPS.

3. Atmospheric Delay Gradients from VLBI and GPS

We have found that modeling azimuthal delay asymmetries (caused by horizontal gradients in atmospheric refractivity) in atmospheric delay improves the precision and accuracy of VLBI geodetic results [MacMillan, 1995; MacMillan and Ma, 1996]. The reason it is important to model gradients is that site vertical and horizontal errors resulting from gradients can be as large as 3-4 mm even observing only down to a 15° elevation limit, which is typical for standard GPS solutions and 6-7 mm at 7° for VLBI. In addition, horizontal gradient estimates are also useful meteorological products. To study the horizontal spatial variation of atmospheric delay, we ran an array of 13 GPS receivers around the VLBI antenna at Goddard. The GPS receivers were at distances ranging from 3 km to 200 km from the Goddard IGS site at which VLBI and GPS antennas are collocated. The purpose of this experiment was to measure the spatial variation of the atmosphere sensed by the VLBI antenna. [MacMillan and Clark, 1995].

Spatial variation of GPS zenith tropospheric delay estimates was determined to get a measure of the significance of variations as a function of spatial scale. This will be useful in assessing the practical use of water vapor retrievals in weather modeling and prediction. We found that spatial variation is significant compared to measurement error for sites separated by more than 10 to 20 km. The zenith delay difference between sites can be approximately converted to a gradient parameter to compare with VLBI delay gradient estimates. The agreement is at the 30-40% level. This type of comparison is difficult to make because it depends on the vertical refractivity profile and specifically whether the gradient is due to the hydrostatic or water vapor component of the refractivity. Estimating gradients from data from GPS sites collocated with VLBI antennas would allow a more direct comparison between techniques.

Presentations and Publications of DOSE Work

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Report Documentation Page

1. Report No.		2. Government Accession No.		3. Recipient's Catalog No.	
4. Title and Subtitle Dynamics of the Solid Earth Final Report				5. Report Date 31 January 1996	
				6. Performing Organization Code	
7. Author(s) Dr. Curtis A. Knight				8. Performing Organization Report No. 002	
				10. Work Unit No.	
9. Performing Organization Name and Address Interferometrics Inc. 14120 Parke Long Court Chantilly, VA 22021				11. Contract or Grant No. NAS5-31747	
				13. Type of Report and Period Covered Final Report 6 Jun 92 - 31 Dec 95	
12. Sponsoring Agency Name and Address Goddard Space Flight Center Earth Sciences Procurement Office Greenbelt, MD 20771				14. Sponsoring Agency Code	
15. Supplementary Notes					
16. Abstract The work performed under this contract provides for the improvement of modeling of troposphere propagation delay in VLBI data, defining of required accuracy of ancillary data type(s) to measure tropospheric behavior and to develop a clear correspondence between tropospheric behavior and the quality of geodetic VLBI measurements.					
17. Key Words (Suggested by Author(s)) VLBI GPS Tropospheric delay				18. Distribution Statement	
19. Security Classif. (of this report) Unclassified		20. Security Classif. (of this page) Unclassified		21. No. of pages 4	
				22. Price \$100,000.00	